CHAPTER 22

AERIALS AND TRANSMISSION LINES

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SECTION 1 : INTRODUCTION

Aerials and transmission lines differ from simple electrical networks in that their inductance, capacitance and resistance are not lumped but are distributed over distances such that the time required for electrical energy to travel from one part to another has to be taken into account. In a single chapter it is, of course, impossible to attempt to give a theoretical treatment of these devices. What will be done will be to present some useful formulae, a few physical pictures of the processes which occur and some results of practical experience with aerials and transmission lines.

SECTION 2 : THE TRANSMISSION LINE

(i) Introduction (ii) The correct termination for a transmission line (iii) Impedance-transforming action of a transmission line.

(i) Introduction

A transmission line consists of an arrangement of electrical conductors by means of which electromagnetic energy is conveyed, over distances comparable with the wavelength of the electromagnetic waves, from one place to another. The theory of transmission lines provides a link between circuit theory and the field theory of electromagnetic waves inasmuch as the properties of such lines may be determined either from the picture of a transmission line as a filter network with an infinite number of elements, or from the picture of electromagnetic waves guided between (usually) a pair of conducting surfaces.

Some of the properties of transmission lines will now be given.

(ii) The "correct" termination for a transmission line

A uniform transmission line has what is called a " characteristic impedance ". This is the impedance that would be measured at the end of such a line if it were infinitely long. The importance of this characteristic impedance lies in the fact that if any length of line is terminated in an impedance of this value, then all the energy flowing along the line is absorbed at the termination and none is reflected back along the line. A result of this is that the input impedance of any length of transmission line terminated in its characteristic impedance is equal to the characteristic impedance. At radio frequencies, the characteristic impedance of all normally-used types of transmission line is almost purely resistive.

The value of the characteristic impedance for a low-loss line is

$$Z_0 = \sqrt{L/C} \tag{1}$$

where L and C are the distributed inductance and capacitance per unit length of the line. The velocity of propagation of electromagnetic waves along such a line is

$$v = 1/\sqrt{LC} \tag{2}$$

With air as the dielectric, $v = 3 \times 10^8$ metres per second, which is the velocity of light*. For other dielectrics

$$v = 3 \times 10^8/\sqrt{K} \text{ metres per second} \tag{3}$$

where K = dielectric constant.

In cables with polythene dielectric, for example, $K = 2.2$ and v is therefore 0.67 of the velocity of light. This means that the wavelength of the waves in the cable is only 67% of the wavelength in air.

For a low-loss transmission-line the characteristic impedance may be found if C and L are determined. Actually it is not necessary to determine both—one is sufficient.

If we combine (1) and (2) we obtain

$$Z_0 = 1/vC = vL. \tag{4}$$

For a transmission line consisting of a pair of parallel conductors

$$Z_0 = \frac{276}{\sqrt{K}} \log_{10} \frac{d}{r} \text{ ohms} \tag{5}$$

where d is the distance between the centres of the conductors and r is the radius of each conductor.

For a co-axial line

$$Z_0 = \frac{138}{\sqrt{K}} \log_{10} \frac{r_1}{r_2} \tag{6}$$

where r_1 is the inside radius of the outer conductor and r_2 is the outside radius of the inner conductor.

(iii) Impedance-transforming action of a transmission line

If the line is terminated in an impedance Z_L which is not equal to the characteristic impedance Z_0 of the line (or, in other words, the load is not matched to the line), then the energy is not completely absorbed at the termination, but some is reflected back along the line. As a result of this, **standing waves** are formed on the line, and the value of the input impedance to the line depends on the length of the line. The ratio of the voltage (or current) in the backward wave to that in the forward wave is called the **reflection coefficient** and has a value

$$k = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{7}$$

The **standing-wave ratio** in the line is the ratio of the maximum to the minimum voltage (or current) that appears at points along the line. (The distance between a maximum and an adjacent minimum is one quarter wavelength).

The standing-wave ratio has a value—

$$\rho = \frac{1 + |k|}{1 - |k|} \tag{8}$$

If Z_L is resistive and has a value R_L, then (8) becomes

$$\rho = R_L/Z_0 \text{ or } Z_0/R_L \tag{9}$$

depending on whether R_L is greater or less than Z_0.

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*A more precise value is 2.9979×10^8 metres/sec.—see Chapter 9 Sect. 11(iii) and Ref. E1.

For a transmission-line having no dissipation, the **input impedance** Z_i is given by

$$Z_i = Z_0 \frac{Z_L \cos \beta l + j Z_0 \sin \beta l}{Z_0 \cos \beta l + jZ_L \sin \beta l} \tag{10}$$

where $\beta = 2\pi/\lambda$, λ being the wavelength of the waves in the transmission line and l the length of the transmission line.

If l is equal to any integral number of half waves, then

$$\cos \beta l = \cos n\pi = \pm 1$$
$$\sin \beta l = 0$$
$$\text{and } Z_i = Z_L, \tag{11}$$

i.e. the input impedance is equal to the load impedance irrespective of the value of Z_0.

On the other hand, if the line has a length equal to an odd integral number of quarter-waves, then

$$Z_i = Z_0{}^2/Z_L \tag{12}$$

This relation is interesting, because it shows the basis of the **quarter-wave transformer**, which is used extensively. The section of line will match a generator to a load if Z_0 is chosen to be equal to the square-root of the product of the generator and load impedances.

SECTION 3 : AERIALS AND POWER TRANSFER

(i) Introduction (ii) Power transfer.

(i) Introduction

The function of a receiving aerial is to collect electromagnetic energy which is passing through the space surrounding the aerial, and to pass this energy into a radio receiver.

(ii) Power transfer

We consider first the simplest case of energy transfer between a transmitter and a receiver, where **two straight dipole aerials** are placed a large number of wavelengths apart and are far removed from any reflecting surface, such as the earth. Suppose that one aerial is energized by a transmitter, and that the other is connected to a receiver. If the power of the transmitter remains fixed, then we find that the power appearing at the receiver is dependent on a number of factors—

(a) The received power is greatest when the aerials are parallel to each other (for short aerials, the maximum occurs when the axis of each aerial is perpendicular to the line joining the centres of the two aerials ; for aerials longer than one half-wave length, this is not necessarily so).

(b) The received power is inversely proportional to the square of the number of wave-lengths between transmitting and receiving aerials.

(c) For aerials less than one half-wave in length, the power received is independent of the length of either aerial, provided the aerials can be matched **without loss** to the transmitter or receiver. In practice, however, aerials very short compared with a wave-length are characterised by high ohmic losses.

Paragraphs (b) and (c) may be summarized quantitatively as follows.

If P_T is the power emitted from a dipole aerial (less than half-wave in length) and P_R is the power available for transfer from the receiving aerial to a receiver, and n is the number of wavelengths between transmitting and receiving aerials, then

$$\frac{P_R}{P_T} = \left(\frac{0.119}{n}\right)^2 \tag{13}$$

Although this formula applies only when the aerials are situated in free space (or, as is shown later, when the transmitting and receiving aerials are of the short vertical type, situated close to a flat perfectly conducting earth), the formula is useful in illustrating a very important fact, which is, that **in the transfer of power between two aerials, the number of wave-lengths, rather than the distance, is the significant parameter.** As an illustration of this we may compare the energy available at a receiver when the frequency of the emitted wave is (a) 600 Kc/s and (b) 150 Mc/s. We assume that the energy radiated in each case is 1000 watts and the distance between transmitter and receiver is 20 kilometres.

On applying the formula (13) we find that in the medium-frequency case, the power available at the receiver is 8.8 milliwatts, while in the v-h-f case the power available is only 0.142 microwatts.

This means that if both signals are to be amplified to produce, say 1 watt at the detector then the amplification required in the first case is approximately 20 decibels while in the second, it is nearly 70 decibels.

These figures partly explain why a crystal receiver is very effective for long-wave reception, whereas a receiver required for v-h-f work usually has a large number of stages of amplification.

SECTION 4 : CHARACTERISTICS OF AERIALS

(i) Effective area of a receiving aerial (ii) The power gain of an aerial (iii) The beam-width of an aerial.

(i) Effective area of a receiving aerial

The radio-frequency power passing through a unit area placed at right angles to the direction from a short dipole transmitting aerial does not (in free space) depend on the frequency. Its value is given by

$$\Phi = \frac{3P_T}{8\pi d^2} \text{ watts per square metre} \tag{14}$$

if the distance d from the transmitting aerial is given in metres, and P_T is in watts. Why is the power available at the receiver dependent on the frequency? The reason is that the **effective area** for capture of energy by the receiving aerial depends on the frequency.

The power available at the receiver is

$$P_R = \Phi A \tag{15}$$

where A is defined as the " effective area " of the receiving aerial.

If we substitute values of P_R and Φ from (13) and (14) we find that the effective area for a short dipole is $0.119\lambda^2$. In the example given above, A is approximately 30 000 square metres in one case and is less than 0.5 square metre in the other. The reason for the enormous difference in the energy available at the receiver in the two cases is now clear.

In the following table, the effective areas of various types of aerial are given :

TABLE 1

Type	Effective Area
Short dipole	$3\lambda^2/8\pi$ or approx. $0.119\lambda^2$
Half-wave dipole	$0.130\lambda^2$
Half-wave dipole with reflector	$0.25\lambda^2$ to $0.50\lambda^2$ (depending on spacing)
Broadside array with reflectors	Physical area, approximately
Broadside array, without reflectors	Physical area/2, approximately
Short vertical aerial near earth	$3\lambda^2/16\pi$

It will be seen from the table that the effective area for capture of electromagnetic energy by a short dipole is approximately equal to an area bounded by a circle which is at a radial distance of $\lambda/1.6\pi$ from the dipole. The physical significance of this is that such a circle very roughly forms the boundary between the region in which the local induction field of the aerial predominates and the region in which the radiation field is the major component. Hence we can picture the aerial as capturing the energy which falls within the region in which the induction field of the aerial is of significant magnitude.

A broadside array of dipoles with a reflecting curtain can absorb all the energy that falls on it. Without the reflectors, it absorbs only half the incident energy and radiates one quarter back towards the transmitter and one quarter in the opposite direction. A similar effect occurs with a dipole. If it absorbed all the energy available to it and reradiated none, then its effective area would be double the value given in Table 1. A reflector is required to achieve this.

(ii) The power-gain of an aerial

The power-gain of a receiving aerial is the ratio of the power appearing at the input terminals of a receiver which is attached to the aerial to the power that would appear at the receiver if the aerial were replaced by a simple type of aerial (usually a half-wave dipole).

The **power gain,** G, of an aerial, therefore, must be equal to the ratio of the effective area A of the aerial to that of the comparison aerial.

With the half-wave dipole as the comparison aerial, we have

$$G = A/0.130\lambda^2 \tag{16}$$

As an example we may consider the case of an array of N half-wave elements spaced one half-wave length and arranged in the form of a rectangular curtain. Then from Table 1 we find

$$A \approx \text{Physical area}/2 \approx (N/2)(\lambda/2)(\lambda/2) = N\lambda^2/8 \tag{17}$$

Therefore $G \approx N\lambda^2/1.04\lambda^2 \approx N$ (18)

i.e. the power-gain of a broadside array of half-wave elements is approximately equal to the number of elements in the array.

(iii) The beam-width of an aerial

For a directional aerial having one major lobe in its directivity pattern there is a rough but useful rule to determine the angular width of this lobe. If the aerial has a breadth of n wave-lengths in any particular direction and the beam-width θ of the main lobe is measured in the same plane, then

$$\theta \approx 60/n \text{ degrees} \tag{19}$$

SECTION 5 : EFFECTS OF THE EARTH ON THE PERFORMANCE OF AN AERIAL

(i) Introduction (ii) A perfectly-conducting earth (iii) An imperfectly-conducting earth (iv) The attenuation of radio waves in the presence of an imperfectly-reflecting earth.

(i) Introduction

In the previous section the effect of reflecting surfaces has been disregarded. In practice, these effects must be taken into account, except in rare cases. The two " surfaces " to be considered are the earth and the ionosphere. We deal here with the effect of the earth.

(ii) A perfectly-conducting earth

The effect of the earth on the propagation of radio-waves is complicated and no attempt will be made here to treat it at all fully. As a first approximation one can consider the earth as a perfectly conducting flat surface. This enables one to use a device which simplifies the treatment considerably. One imagines an image of the aerial in the reflecting surface, and then the problem may be treated as one in which the aerial and its image are situated in free space. (The sign of the instantaneous potentials in the image are reversed from those in the aerial).

In Fig. 22.1 are shown the effects of the earth on the field pattern of a short vertical aerial and of a short horizontal dipole. It will be seen that the earth has no effect on the field pattern of the vertical aerial apart from removing the lower half of the pattern. With the horizontal aerial, however, there is complete cancellation of the waves in the horizontal plane and the resultant effect is zero.

The conclusion may be drawn from the diagram that where waves are arriving at the aerial in directions parallel to the plane of the earth, then one would expect a vertical aerial to be very effective while a horizontal aerial would be ineffective. (This applies to a transmitting as well as to a receiving aerial). It will be seen later that this conclusion does not fit the facts, in all cases, because the earth is not a perfect conductor. At medium and low radio-frequencies, however, it is in agreement with the facts—horizontal aerials are of no use in communicating between two points both close to the earth.

When waves are arriving at the aerial in directions inclined to the horizontal (as, for example, in the case of short-wave communication via the ionosphere) then either horizontal or vertical aerials may be used. If the distance between transmitter and receiver is not great, however, then the waves will be arriving at nearly vertical incidence and the horizontal aerial will be superior, provided that it is placed at a suitable height above the earth. The height at which the aerial should be placed above the earth depends on the angle of elevation of the waves which are to be received. The height is different for horizontal and vertical aerials.

In Fig. 22.1, for an angle of elevation θ, the distance d between the path lengths of waves to the aerial and to its image should be equal to an even number of half-waves in the case of a vertical aerial, and an odd number of half-waves in the case of a horizontal aerial. Simple trigonometry shows that this corresponds to a height h given by

$$h = n\lambda/(4 \sin \theta) \qquad (20)$$

where n is an even integer for a vertical aerial and an odd integer for a horizontal aerial.

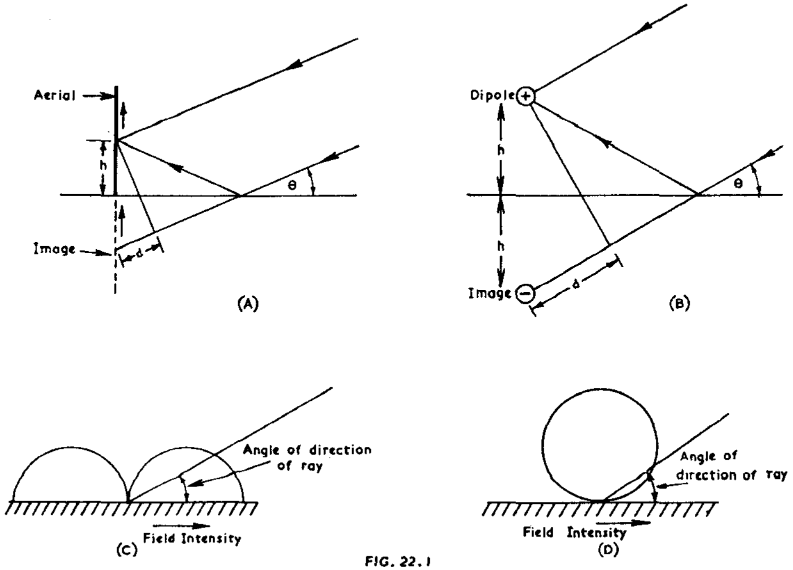

FIG. 22.1

Fig. 22.1. *Effects of the earth on the field pattern of a short vertical aerial* (A) *and of a short horizontal dipole* (B). *Both* (A) *and* (B) *are cross-sectional views, and in* (B) *the sign* + *indicates direction of current into the paper while the sign* − *indicates the opposite direction. Polar diagrams of a short vertical aerial and a short horizontal dipole, both close to earth, are shown in* (C) *and* (D) *respectively.*

(iii) An imperfectly-conducting earth

The propagation of radio-waves close to the surface of a finitely conducting earth has been studied theoretically for many years. Zenneck first produced a solution to the problem, and later Sommerfeld gave a more accurate analysis. Unfortunately, the incorrectness of Zenneck's analysis combined with a small error in Sommerfeld's, created some confusion that has persisted until the present day. As a result of the errors, it appeared that a special type of wave was propagated in the vicinity of the ground-plane. This wave was called a " surface-wave." It is known now, that this Zenneck " surface-wave " does not exist, but the name still appears in the literature on wave propagation. It is applied to the waves that travel between transmitting and receiving aerials when both are close (in terms of a wavelength) to the surface of the earth, as for example, in medium-wave broadcasting. When the aerials are raised several wave-lengths above earth, then the waves travelling between them are called " space-waves." These terms are artificial, but they serve some purpose in that they indicate that the conditions of propagation between two aerials placed close to the earth, are markedly different from those between two aerials elevated several wave-lengths above the earth's surface (as in v-h-f broadcasting).

In the conditions of propagation to which the term " surface-wave " is applied, vertical aerials are superior to horizontal aerials. Thus vertical aerials are always used in medium-frequency broadcasting. (The horizontal portion of a medium-frequency receiving or transmitting aerial plays no useful part, except to increase the efficiency of coupling to the receiver or transmitter).

When the aerials are raised several wave-lengths above the earth, as is usually the case in v-h-f communication, then horizontal and vertical aerials have roughly equal effectiveness.

When waves are not arriving at the aerial in a horizontal direction, then the difference between an imperfectly conducting earth and a perfectly conducting one is not so marked. Hence for short-wave communication one can treat the earth as a perfect conductor without introducing serious error in the calculations.

(iv) The attenuation of radio-waves in the presence of an imperfectly-reflecting earth

At short distances from a transmitting aerial the resistivity of the earth does not have a major effect on the energy reaching the vicinity of the receiving aerial. The principal effect of the earth is that the energy flowing through unit area placed at right angles to the line of propagation is doubled. The reason for this is that the transmitting aerial is now emitting its energy into a hemisphere instead of into a full sphere as was the case in free-space propagation.

Instead of the relation (14) we have now

$$\Phi = 3P_T/4\pi d^2 \qquad (21)$$

where the symbols have the same meaning as in formula (14).

For a similar reason the effective area for capture of radiation by the receiving aerial is half that of the free-space case. For a short vertical aerial the effective area is

$$A = 3\lambda^2/16\pi. \qquad (22)$$

The effects at the transmitting and receiving aerials, however, are such that the power attenuation between the two is the same as in the free-space case, so (13) is still applicable.

As the distance between the two aerials is increased, it is found that the attenuation actually found between transmitter and receiver becomes increasingly larger than that given by (13). This is the result of both the finite conductivity and of the curvature of the earth.

For the range of frequencies used in medium-wave broadcasting, and for earth of average conductivity ($\sigma = 7 \times 10^{-14}$ e.m.u.), values of the power-flux per unit area at the receiver are shown in Fig. 22.2.

Such curves are frequently given in terms of the strength ϵ of the electric field of the wave. To convert this into power-flux per unit area, one may use the relation

$$\epsilon = \sqrt{377\Phi} \text{ volts per metre} \qquad (23)$$

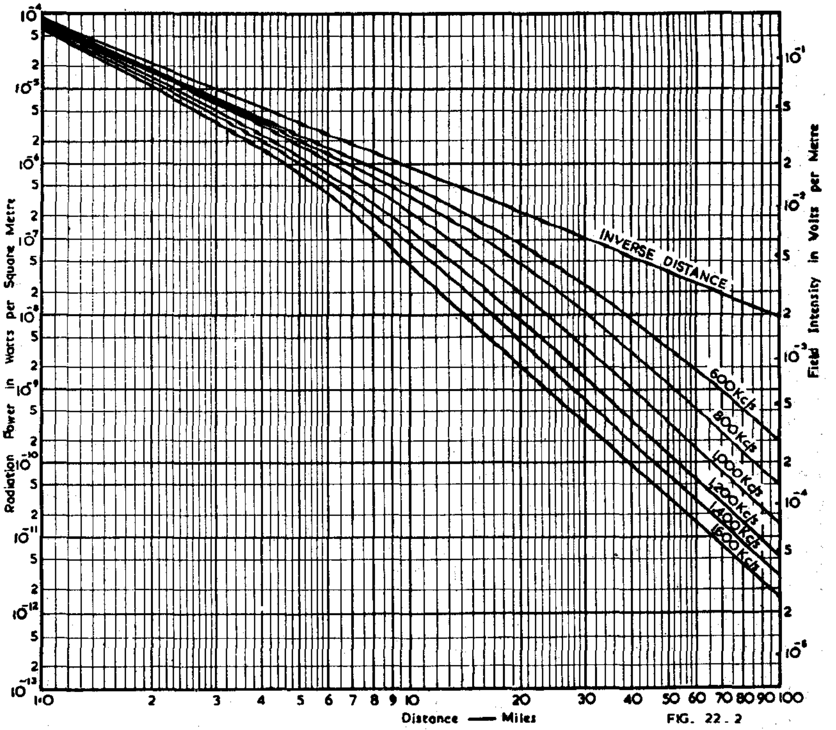

Fig. 22.2. *Attenuation at medium frequencies of the radiation from a transmitter (1 KW radiated, short aerial, average earth conductivity,* $\sigma = 7 \times 10^{-14}$ *e.m.u.,* $\epsilon = 15$).

where Φ is expressed in watts/metre^2.

Sometimes it is required to know the strength H of the magnetic field of the wave. This is related to the electric field by the expression

$$H = (\epsilon/377) \text{ ampere-turn/metre*} \qquad (24)$$

As a matter of interest, it may be noted that ϵ and H are analogous to voltage and current in electrical circuit theory. On this analogy the number 377 appears to denote a resistance, and is called the **intrinsic resistance of free space.**†

At very-high-frequencies, the attenuation of waves between two aerials close to the ground is rapid. This corresponds to the case of the so-called " surface waves " referred to in the previous section. Fortunately it is not difficult, at these frequencies, to raise the transmitting and receiving aerials several wave lengths above ground and achieve the conditions for " space-wave " propagation, where the attenuation is very much less.

For such conditions, a rough but useful formula for the attenuation is given by

$$P_R/P_T = (1.5\ h_T h_R/n^2)^2 \qquad (25)$$

where h_T and h_R are the heights (in wavelengths) above earth of the transmitting and receiving aerials, and the other symbols are the same as in (13).

More accurate values may be found by using Figs. 22.3, 22.4 and 22.5.

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*The ampere-turn/metre is the unit of magnetic field strength in the Rationalized Meter Kilogram Second (M.K.S.) system of units.

1 ampere-turn/metre $= 4 \times 10^{-3}$ e.m.u. (oersted).

† Note : ϵ/H in e.m.u. $=$ c ; ϵ/H in e.s.u. $= 1/c$.

ϵ expressed in e.s.u. $= H$ expressed in e.m.u. Refer to Chapter 38 Sect. 1(ii) on electrical and magnetic units.

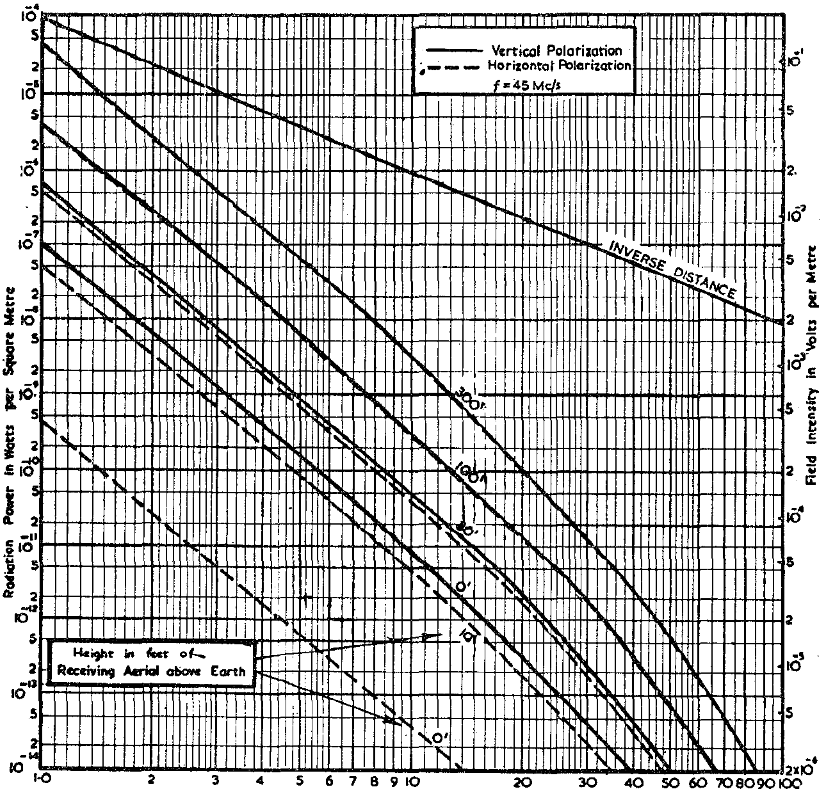

FIG. 22.3

Fig. 22.3. Effect of raising the receiving aerial above the earth (1 KW at 45 Mc/s radiated over earth with conductivity $\sigma = 10^{-13}$ *e.m.u. and transmitting aerial 30 feet above the earth). The same curves also apply when the transmitting and receiving aerials are transposed.*

Fig. 22.3 shows the effect of raising the aerial above the earth* for a frequency of 45 Mc/s, and indicates that unless the aerials are close to the earth, horizontal and vertical polarizations have practically equal effectiveness.

Fig. 22.4 and 22.5 for frequencies of 75 and 150 Mc/s were derived by T. L. Eckersley for vertically polarized waves, but may be used also for horizontally polarized waves with little error when the aerials are at heights above earth corresponding to normal practice.

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*An infinitely short dipole has been assumed.

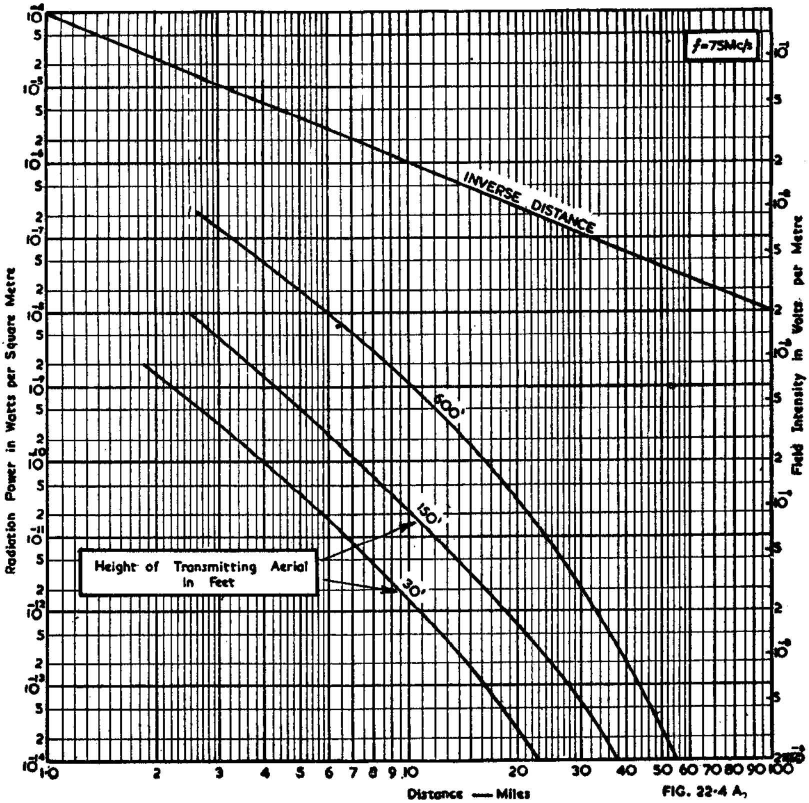

FIG. 22·4 A,

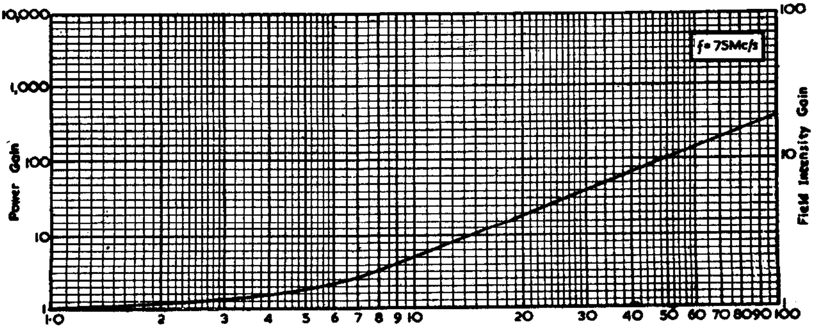

FIG. 22.4 B

Fig. 22.4 (A) *Attenuation at* 75 *Mc/s of the radiation from a transmitter* (1 *KW radiated over earth with* $\sigma = 10^{-13}$ *e.m.u.,* $\epsilon = 5$, *with receiving aerial at zero height*) ; (B) *Multiplying factor for height of receiving aerial above earth.*

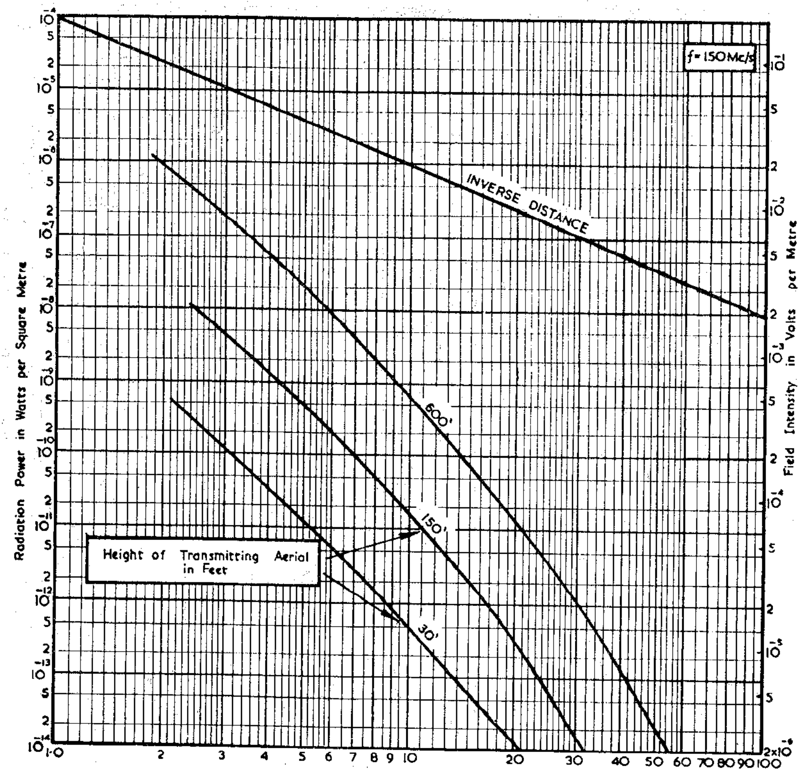

FIG. 22.5 A

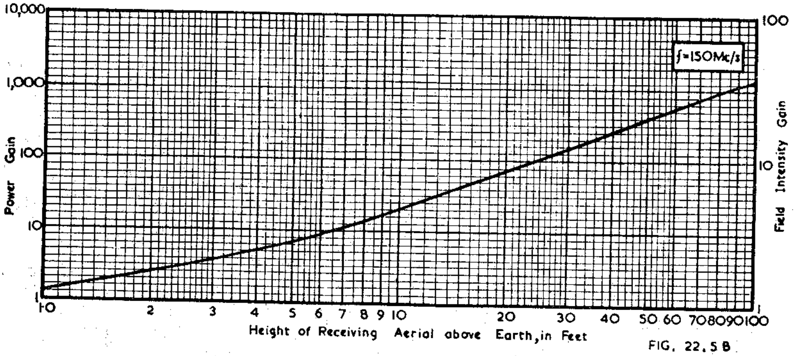

FIG. 22.5 B

Fig. 22.5. (A) *Attenuation at* 150 *Mc/s of the radiation from a transmitter* (1 *KW radiated over earth with* $\sigma = 10^{-13}$ *e.m.u.*, $\epsilon = 5$, *with receiving aerial at zero height*) ; (B) *Multiplying factor for height of receiving aerial above earth.*

SECTION 6 : THE EFFECT OF THE IONOSPHERE ON THE RECEPTION OF RADIO SIGNALS

Radio propagation over long distances on the earth is possible because of the presence of layers of ionized gas in the higher atmosphere of the earth. Signals reflected from the ionosphere are used exclusively in short-wave reception.

The principal reflecting layers in the ionosphere are the E and F_2 layers, situated at roughly 60 miles and 200 miles, respectively, above the surface of the earth. The E layer is a poorly reflecting surface and hence short-wave communication almost exclusively takes place via the F_2 layer. In designing a receiving aerial for short-wave communication, one must calculate the angle of elevation at which signals will arrive at the aerial, and then use the relation (20) to determine the height at which the aerial should be placed above earth. This calculation involves a knowledge of the height of the ionospheric layer, the distance between transmitting and receiving aerials, and the curvature of the earth.

The Australian reader is referred to the " Radio Propagation Handbook " and the " Monthly Ionospheric Predictions " produced by the Ionospheric Prediction Service of the Commonwealth Observatory, for information on communication by way of the ionosphere. In America the equivalent publications are the N.B.S. Circular 465 " Instructions for the use of basic radio propagation prediction " and CRPL-D publication " Basic radio propagation predictions " obtainable from the Central Radio Propagation Laboratory, National Bureau of Standards, Washington, D.C. The English reference is Bulletin A, published by Radio Research Station, National Physical Laboratory.

See also Chapter 8 References 5, 7 and 10.

In medium-wave broadcasting the ionosphere does not reflect any appreciable amount of energy during daylight hours. At night, however, waves are reflected back to the earth from what remains of the E layer (unlike the F layer, the E layer practically disappears at night) and these waves provide a secondary, or fading, service during the night hours over distances of hundreds of miles. Unfortunately, these reflected waves reach the earth also at relatively short distances (50 to 100 miles) from the transmitter and combine with the ground waves to produce a very objectionable type of fading. Hence the primary or non-fading service area of a medium-wave broadcasting station may be less at night than during the day. Aerials that favour signals which arrive horizontally and discriminate against those that arrive from high angles will diminish this undesirable effect. This normally cannot be done very effectively because the height required for the aerial is neither possible nor economical in a receiving installation. The best that can be done is to avoid types of aerials that accentuate this effect. Where night-time fading of signals is encountered, straight vertical aerials should be used. Loop aerials and inverted-L aerials with long horizontal sections should be avoided, and care should be taken that r-f coupling between the power mains and the receiver is kept to a minimum.

SECTION 7 : THE IMPEDANCE OF AN AERIAL

(i) Introduction (ii) Resistive component of impedance (iii) Reactive component of impedance (iv) Characteristic impedance of aerial (v) Examples of calculations (vi) Dipoles (vii) Loop aerials.

(i) Introduction

In the previous sections, the energy ideally available at the receiver terminals has been calculated. This energy is available, however, only if the receiver is matched to the aerial, and if there are no resistive losses associated with the aerial or aerial-earth system.

If the input circuit of a receiver is to be designed to extract the maximum energy from the radio-waves that are passing the aerial, then a knowledge of the component parts of the impedance of the aerial is required.

(ii) Resistive component of impedance

The first part of the aerial impedance to be considered is the resistive part concerned with the coupling between the aerial and the space around it. This is called the **Radiation Resistance** of the aerial and is the resistance that would be measured at the point of maximum current in a tuned aerial, in the absence of resistive losses. If a load resistance of this value is placed in the aerial at the point considered, then the aerial would extract from a passing wave an amount of power equal to the "available power" calculated in the previous sections.

The calculation of the radiation resistance of an aerial is not easy, and in most cases the calculations provide only approximate answers. The reader is referred to standard texts for these approximate methods of calculation.

If the impedance is measured at the base of an ideal vertical aerial, then the resistive component is called the **Base Radiation Resistance.** Values of this for the types of aerial commonly used in medium-frequency reception are given in Fig. 22.6.

If the r-f resistance at the base of an aerial is measured, it will be found to be greater, in general, than the calculated radiation resistance. The difference represents the loss resistance associated with the aerial-earth system. For a short aerial with small radiation resistance, the loss resistance may be many times greater than the radiation resistance. With such an aerial one can extract only a fraction of the power ideally available at the terminals of the aerial.

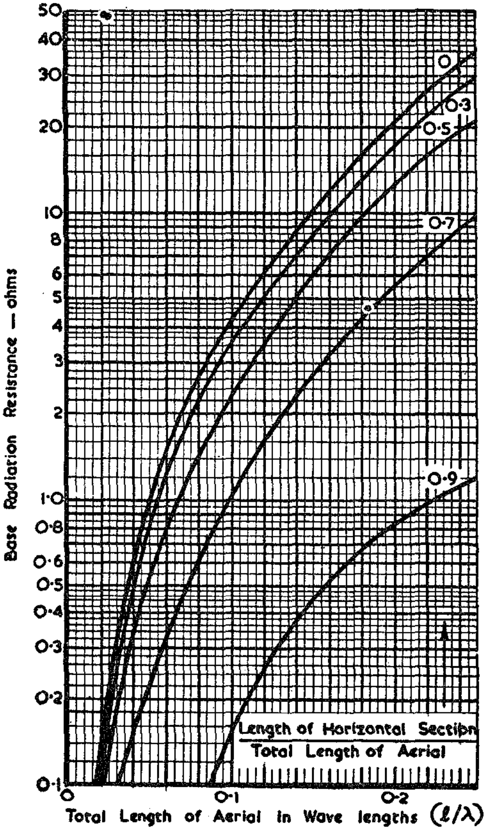

FIG. 22.6

Fig. 22.6. *Base radiation resistance of an inverted L aerial.*

If we wish to calculate the power that may be extracted from the aerial in the presence of resistive losses we proceed as follows.

The power P_R ideally available at the aerial may be calculated and we can use information such as that given in Fig. 22.6 to find the radiation resistance R_R of the aerial. By measuring the base resistance and subtracting R_R from this we are left with R_L, the equivalent series loss resistance of the aerial-earth system. The equivalent circuit is shown in Fig. 22.7. It may be noted that we have not yet calculated e, the equivalent e.m.f. induced in the aerial by the radio-wave. This can be done easily however, because we know the resistance R_R and the power P_R that would be generated in a load resistance of this value if R_L were absent. Across such a load we would have a voltage of $e/2$.

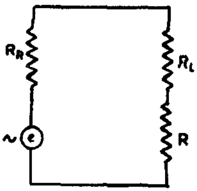

FIG. 22.7

Fig. 22.7. Equivalent circuit of aerial-earth system.

Hence $e = 2\sqrt{P_R R_R}$ (25A)

When R_L is not negligible, then the load resistance R must be increased to $R_R + R_L$ for maximum power transfer. In this case, the power in the load is

$$P' = \left(\frac{e}{2}\right)^2 \Big/ (R_R + R_L) \tag{26}$$

Hence the ratio of power actually extracted from the aerial to that ideally available (or the **radiation efficiency of the aerial**) is given by

$$P'/P_R = R_R/(R_R + R_L). \tag{27}$$

To take a simple example, suppose that we have a vertical aerial of 1/16 wavelength, and an earth resistance of 20 ohms and that we wish to calculate the radiation efficiency of the aerial.

From Fig. 22.6 we find $R_R = 1.6$ ohms, and we are given $R_L = 20$ ohms. Then $P'/P = 0.08$, which is the radiation efficiency of the aerial.

(iii) Reactive component of impedance

So far, only the resistive component of the base impedance of the aerial has been mentioned and we have assumed that the reactive part has been tuned out. It is most desirable that we should be able to calculate this reactive component, at least roughly, from the aspects of both the design of the input circuit of the receiver and the estimation of losses introduced by the tuning reactances.

A simple way to make an approximate calculation of the reactance of an aerial, is to treat it as a section of transmission line. We can simplify this treatment still further by neglecting the resistive component of the aerial impedance and by assuming that the transmission line has no loss. (This treatment breaks down when the base of the aerial is close to the point of minimum current of an aerial, but this case is very seldom met in an aerial designed for reception). Hence we can use the simple transmission line formula (10).

If the aerial is a straight wire, then this may be taken as an open circuited length of line. The terminating impedance Z_L is then infinite and (10) becomes

$$Z_i = X_i = -jZ_0 \cot \beta l \tag{28}$$

This formula can be applied also to an inverted L aerial, by neglecting the bend in the aerial and by taking l as the total length of wire in the aerial. If the aerial has a more elaborate type of capacitance top, then one can proceed as follows. Imagine the capacitance top broken at the point at which it joins the downlead of the aerial. Use (28) to calculate Z_i for each section of the capacitance top, then combine in parallel the values of Z_i. The resultant is then the terminating impedance Z_L of the aerial downlead. The impedance of this is then obtained from (10).

(iv) Characteristic impedance of aerial

As yet, we have given no indication of the value of characteristic impedance Z_0 to be assigned to the aerial. Various approximate formulae are available for this, but that of Steinmetz is possibly the best. This is

$$Z_0 = 138 \log_{10} (\lambda/d) - 104 \text{ ohms} \tag{29}$$

where λ is the wave-length
and d is the diameter of the aerial conductor (or cage) measured in the same units as λ.

(v) Example of calculations

The following worked example uses much of the work covered so far in this chapter.

Example

A receiving aerial of the inverted-L type has a horizontal top section of 50 ft. length and a 30 ft. vertical downlead. The aerial conductor is composed of 7/.029 in. copper wire. (a) What is the input impedance of the aerial at a frequency of 1000 Kc/s, if the equivalent series earth resistance is 20 ohms? (b) What voltage will appear at the input terminals of a receiver, matched to the aerial, if the receiving aerial is at a distance of 20 miles from a transmitter? The transmitter has a short aerial (less than quarter-wave) and radiates 500 watts. The ground between transmitting and receiving aerials has a conductivity of 7×10^{-14} e.m.u.

(a) Calculation of input impedance

The length of conductor is 80 feet or 24.4 metres, therefore $l/\lambda = 24.4/300 = 0.0813$.

From (28), $X_i = -jZ_0 \cot 2\pi l/\lambda$.

We obtain Z_0 from (29):

$Z_i = 138 \log_{10} 1.36 \times 10^5 - 104 = 603$ ohms

and $2\pi l/\lambda = 29.3°$.

Therefore $X_i = -j\ 603 \cot 29.3° = -j\ 1070$ ohms.

Next, to obtain R_R we use Fig. 22.6. For this aerial the ratio of the horizontal portion of the aerial to the total length is 0.625. By interpolation between plotted values we find that R_R is approximately 1.0 ohm. The series loss resistance is given as 20 ohms, hence the total resistance at the base is 21 ohms.

The base impedance of the aerial is then

$Z_i = 21 - j\ 1070$ ohms.

(b) Calculation of voltage at receiver terminals

From Fig. 22.2 we see that at the given frequency and distance the power flux per unit area Φ is 2.0×10^{-8} watts/m² for a radiated power of 1 KW. Hence Φ is 1.0×10^{-8} for 500 watts radiated. The effective area of the aerial is given in Table 1 as $3\lambda^2/16\pi$. Hence the power ideally available is

$P_R = 1.0 \times 10^{-8} \times 3 \times 300^2/16\pi$

$= 0.535 \times 10^{-4}$ watts.

From (25A) we find that the e.m.f. induced in the aerial (referred to the base radiation resistance) is $e = 2\sqrt{P_R R_R} = 1.46 \times 10^{-2}$ volts or 14.6 millivolts.

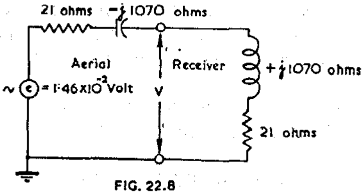

FIG. 22.8

Fig. 22.8. Equivalent circuit of aerial and input circuit of the receiver.

The voltage appearing at the aerial terminals will be greater than the induced e.m.f. because of the highly reactive impedance of the aerial. The equivalent circuit of the aerial and input circuit of the receiver are shown in Fig. 22.8. We see that the aerial current is

$i = 1.46 \times 10^{-2}/42$ and the voltage at the receiver terminals is approximately

$V = i\ 1070 = 0.373$ volt.

(vi) Dipoles

The second type of aerial, the impedance of which we may wish to calculate is the dipole aerial. Dipole aerials well removed from the earth may be treated in a manner similar to that of a vertical aerial, because, at least approximately, a vertical aerial with its image forms a dipole aerial. With the vertical aerial we measure the impedance with respect to the neutral point (earth) of the equivalent dipole, so the impedance is only half that of the equivalent dipole. Hence in calculating the impedance of a dipole we can use the results obtained previously, but multiplied by a factor of two. Because a dipole aerial (remote from the earth) has no earth loss, it is in general more efficient than the equivalent vertical aerial with earth return.

The most commonly used variety of dipole aerial is the resonant, or half-wave variety. When remote from earth it has twice the impedance of a quarter-wave aerial, i.e. its impedance is resistive and has a magnitude of 73 ohms. When in the vicinity of the earth, the impedance depends on the height above earth. The variation is shown in Fig. 22.9.

Reflectors are sometimes used with half-wave aerials at very high frequencies.

In Fig. 22.10 is shown the effect, on the radiation resistance of a half-wave dipole, of the spacing between aerial and reflector, when the latter is tuned to provide maximum forward radiation. (For further information on the effects of reflectors the reader is referred to Ref. 14).

(vii) Loop aerials

Another common type of aerial used in broadcast reception is the loop aerial. With such aerials, the radiation resistance at medium frequencies is normally negligible compared with the loss resistance of the conductors. The aerial may be treated as a lumped inductance, the electrical constants of which can be calculated from well known formulae.

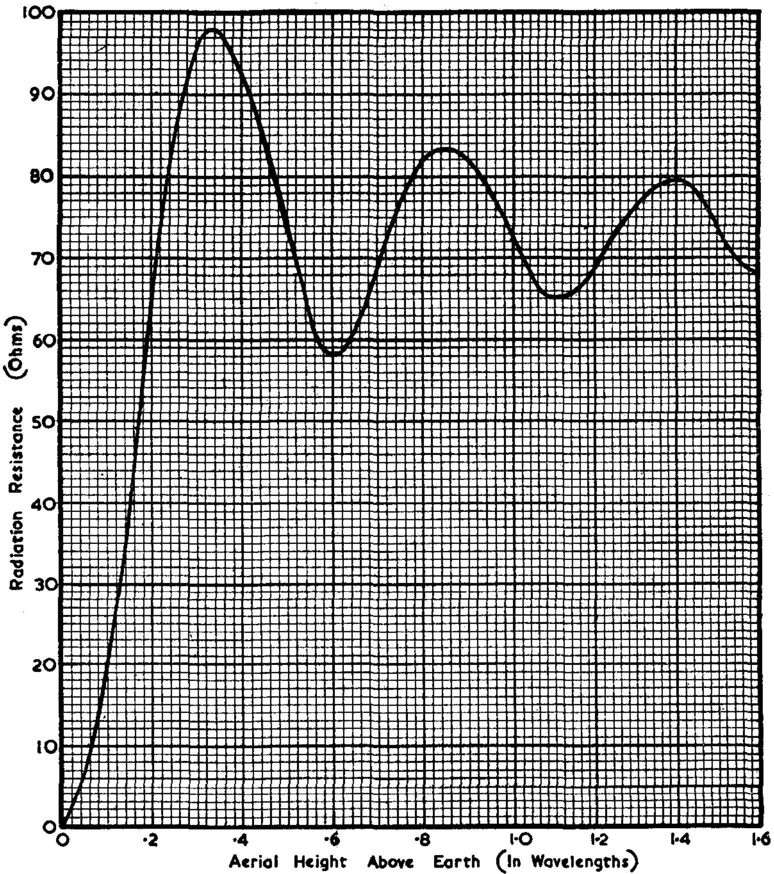

FIG. 22.9

Fig. 22.9. Radiation resistance of horizontal half-wave dipole aerial plotted against height of aerial above the earth.

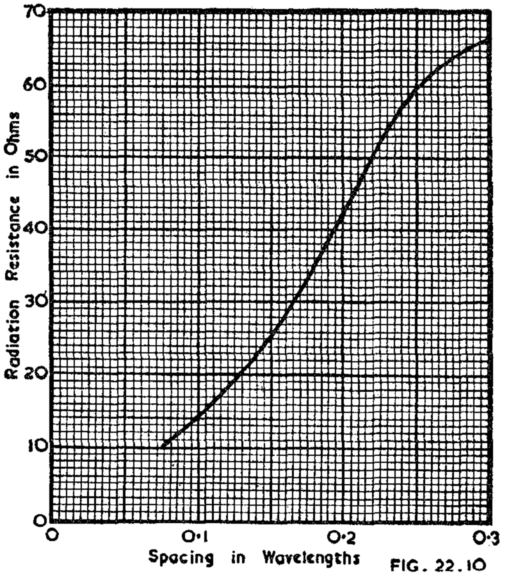

Fig. 22.10. *Radiation resistance of half-wave dipole aerial plotted against spacing between aerial and reflector (tuned to provide maximum forward radiation).*

SECTION 8 : DUMMY AERIALS

When a signal generator is used in adjusting a receiver and in measuring its performance, it is necessary that the generator should present an impedance at the input terminals of the receiver which is equal to that of the aerial. At a single frequency this presents no difficulty ; one may calculate the aerial impedance in the manner shown in the previous section and then add appropriate amounts of resistance and reactance in series with the generator impedance to produce an impedance equal to that of the aerial.

When the receiver is required to be used over a range of frequencies, the production of a dummy aerial that will simulate the aerial is not quite so easy. If the aerial is very short and has a radiation resistance less than the aerial-earth loss resistance, then we can assume the latter to remain constant in value. We have to produce, therefore, a reactance which changes in the same way as that of the aerial. With a very short aerial, the term cot βl in (28) is approximately equal to $1/\beta l$ and we have

$$X_i \approx -jZ_0/\beta l \tag{30}$$

which may be reduced to

$$X_i = \frac{-j}{2\pi fC} \tag{31}$$

where C is the total capacitance of the aerial.

Hence, for such an aerial, the dummy consists of a fixed resistor in series with a fixed capacitor. The impedance of a longer aerial may be represented moderately well over a range of frequencies by a resistor, inductor and capacitor in series, all shunted by a capacitor. For such networks we refer the reader to sources listed in the bibliography.

For standard dummy aerials to be used in receiver testing, see Chapter 37 Sections 1 and 2.

With a receiver designed to operate with a loop aerial, it is not usual to use a dummy aerial when testing the receiver. Instead the aerial is left connected to the receiver and a known e.m.f. is induced in the loop. This is effected by connecting a second loop to a signal generator, and placing the two loops at a suitable distance from each other. The e.m.f. induced in the receiving loop can be calculated if, in addition to the distance, the dimensions of the loops, the number of turns, and the current in the transmitting loop are known.

SECTION 9: TYPES OF AERIAL USED FOR BROADCAST RECEPTION

(i) Introduction (ii) Medium-frequency receiving aerials (iii) Short-wave receiving aerials (iv) V-H-F aerials.

(i) Introduction

Only simple types of aerials, such as are employed in broadcast reception, will be described here; no mention will be made of the more complicated aerials used in point-to-point communication services.

There are three important factors to be considered in the design of an aerial for reception.

(a) Its effective area for the capture of radio energy and its efficiency should be sufficiently great to provide a signal that will override the internal noise of the receiver.

(b) It should be placed as far as possible from sources of noise-interference and, in particular, it should be situated outside the induction field of such generators.

(c) If the radio signal should arrive at the receiver by two different paths (e.g. ground-wave and sky-wave) so that distortion of the received signal results, then the aerial should have sufficient directivity to favour the wanted signal and reject the unwanted one.

At very-high frequencies, the effective area for capture of radio-energy by an aerial becomes so small that the first factor is of great importance. In medium-frequency reception, on the other hand, the second factor is the most important. One reason for this is that at such wavelengths it is not easy to place the aerial outside the induction field of noise sources. This may be seen from the following discussion.

At a distance of several wave-lengths from an aerial the power flowing through unit area falls off as the inverse square of the distance from the aerial. This implies that the field strength of the signal falls inversely as the distance [see (23)] from the aerial. This field is called the radiation field of the aerial. An aerial has also another component of its field which is the predominating one at points close to the aerial, but falls off rapidly and becomes negligible compared with the radiation field at a distance of a few wavelengths from the aerial. This is called the "induction field." At a distance of approximately one sixth of a wavelength ($\lambda/2\pi$) from a short aerial, the components of the induction and radiation field are equal. At shorter distances the intensity of the magnetic field of the aerial increases roughly as the inverse square of the distance from the aerial while the intensity of the electric field increases roughly as the inverse cube of the distance. It is obviously desirable that a receiving aerial should be situated outside this zone around a noise source in which the field intensity increases very rapidly as the distance between receiving aerial and the generator is decreased. This is comparatively easy at very-high frequencies where one sixth of a wavelength may be only one or two feet. At medium frequencies, the corresponding distance is of the order of 50 yards and it may be difficult to place the aerial at such a distance from sources of electrical interference.

(ii) Medium-frequency receiving aerials

Aerials short compared with one half-wave length are generally used. These may be of the straight-vertical, inverted-L or T types. The characteristics of these have been discussed in previous sections.

Very small aerials of this type are sometimes used **indoors.** Such aerials are useful only when the required signals are of large intensity, because these indoor aerials do not fulfil any of the three conditions listed above, except when close to broadcast stations. Besides being inefficient because of their small size, they are also partially shielded by earthed conductors in the house-wiring. They are also very liable to pick up r-f noise carried along the power mains.

Loop aerials are sometimes used in broadcast receivers. When used indoors they have the same drawbacks as the indoor capacitance type aerial, except that if shielded, or balanced with respect to earth, they are less sensitive to inductive interference from nearby sources of r-f noise. The reason for this is that a balanced or shielded loop responds to the magnetic component of the field of an aerial, whereas the capacitance type aerial responds to the electric component. In the radiation field, these two components are equal and are mutually dependent. In the immediate vicinity of an aerial they are not equal, and the electric component increases more rapidly than does the magnetic field as one approaches the aerial. Hence in the vicinity of a radiation source of r-f noise, a loop aerial will pick up less energy than will a vertical aerial.

A loop aerial is more sensitive to waves arriving at steep angles to the plane of the earth than is a vertical aerial. Hence it should not be used where interference between ground and skywaves is experienced. In such conditions a straight vertical aerial is normally the best type of aerial that can be used. In special circumstances, such as occur sometimes in country areas, it is possible to use another type of aerial, called a wave-antenna, to reduce ground-wave - sky-wave interference.

The wave antenna consists of a horizontal wire several wave lengths long suspended a few feet from the ground and directed towards the required broadcast station.

It functions because of an effect that has not been mentioned previously, called wave-tilt. This is the production of a radial component of the electromagnetic field, when the waves are passing over imperfectly conducting ground. This component is picked up by the horizontal wire which, when a wavelength or more long, has maximum directivity along its axis.

(iii) Short-wave receiving aerials

Since short-wave reception usually is concerned with signals of low field intensity, efficient aerials placed well away from sources of interference are required. In an earlier section it was shown that the height of the aerial above ground is also important. Indoor aerials are most unsuitable for short-wave reception. A half-wave dipole placed at the correct height above earth and connected to the receiver by a transmission line provides an efficient receiving system over a restricted range of frequencies. In short-wave reception, however, one is concerned with a range of approximately 3 to 1 in frequency. If the aerial is to provide a reasonably good match to the transmission line or receiver over such a frequency range, then a more elaborate aerial than the simple half-wave type is required.

One way of doing this is to arrange a number of half-wave dipole aerials in the form of a fan and connect them in parallel. Each dipole is tuned to one of the frequency bands allotted for short-wave broadcasting. At resonance the half-wave dipole matches a 70 ohm transmission line. The dipoles that are off resonance provide high and predominately reactive impedances of both signs in parallel with the 70 ohms of the resonant dipole, and have small overall effect.

Such an aerial is connected to the receiver by a balanced transmission line. The receiver must be provided with an input circuit that is also balanced with respect to earth. Alternatively an aperiodic balance/unbalance transformer must be connected between the transmission line and the receiver.

An aerial that has similar characteristics to the one described above, but is not of the balanced type, is shown in Fig. 22.11. It is essentially half of the fan arrangement of dipoles. A common type of co-axial transmission line, having a characteristic impedance of 50 ohms, is suitable for use with this aerial. A few buried radial wires roughly half-wave (at the mid-frequency) in length provide a good earthing system for this aerial.

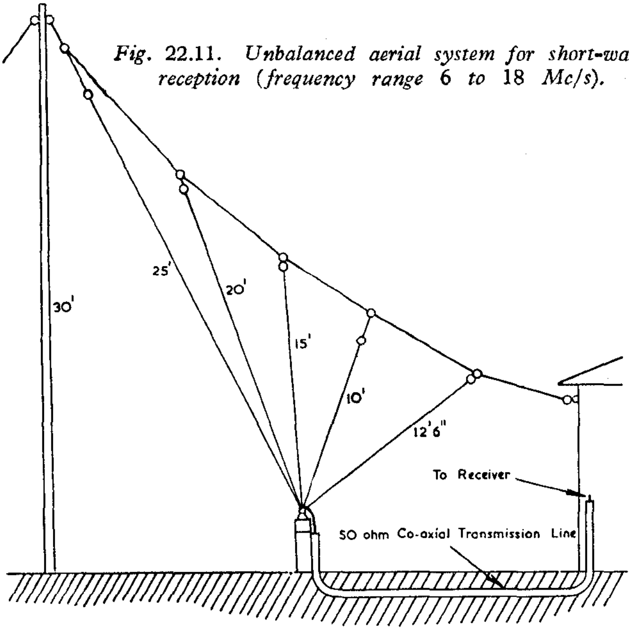

Fig. 22.11. *Unbalanced aerial system for short-wave reception (frequency range* 6 *to* 18 *Mc/s).*

FIG. 22.11

(iv) V-H-F aerials

Because the effective area of an aerial at very high frequencies is small and the amount of energy that it can supply to the receiver is correspondingly small, it is essential that the efficiency of the aerial system should be high. At these frequencies the signal power per unit area at the aerial increases as the square of the height above ground, so the aerial should be placed at the maximum available height.

At very high frequencies the dimensions of the aerial are so small that rigid rods, rather than flexible wires, are used as aerial conductors. This simplifies the problem of the mechanical support for the aerial. Half-wave dipoles and quarter-wave vertical aerials with a counterpoise are the most common arrangements. The provision of a reflector is not difficult and is sometimes advantageous.

Matching the aerial to a transmission line is effected, when necessary, by means of sections of transmission line, rather than by combinations of lumped inductors and capacitors. Space does not permit a treatment to be given here of the great variety of line-sections, stubs and other impedance transforming devices that are in common use at very high frequencies. Nor can we deal with the very large number of varieties of aerial in use. A few of the common types are shown in Fig. 22.12. Of these, (a), (b), (c) and (d) are designed for reception of vertically polarized waves, and (e) and (f) are for horizontally polarized waves. The aerial (a) is the simplest type. It consists of a quarter wave radiator connected to the inner conductor of a co-axial line. Connected to the end of the outer conductor of the coaxial line is a quarter-wave " skirt," which forms, in effect, the second half of a vertical dipole. The impedance of the aerial is roughly 70-75 ohms and matches directly a common type of co-axial transmission-line. The disadvantage of this aerial is that the " skirt " is coupled to the outer conductor of the transmission-line and will pick up signals or noise that are present on this.

Type (b) consists of a vertical quarter-wave aerial with four horizontal quarter wave elements which form an artificial earth plane. The impedance of this aerial is lower than that of the normal quarter-wave aerial above a full earth plane, and it requires a matching stub, or a quarter-wave transformer to transform its impedance to that of a usual type of co-axial transmission line. The impedance of this aerial may be increased by a factor of four, by the device shown at (c), and the necessity of providing an impedance transformer is eliminated. Type (d) is a discone aerial, useful over a wide range of frequencies.

(e) Is the most commonly used type of horizontal aerial. It consists of two quarter-wave arms, one connected to the inner, and one to the outer conductor of a co-axial line. An outer quarter-wave sheath is connected at its lower end to the outer conductor of the co-axial line. The effect of this is to isolate the latter from earth, and hence preserve the balance of the aerial with respect to earth.

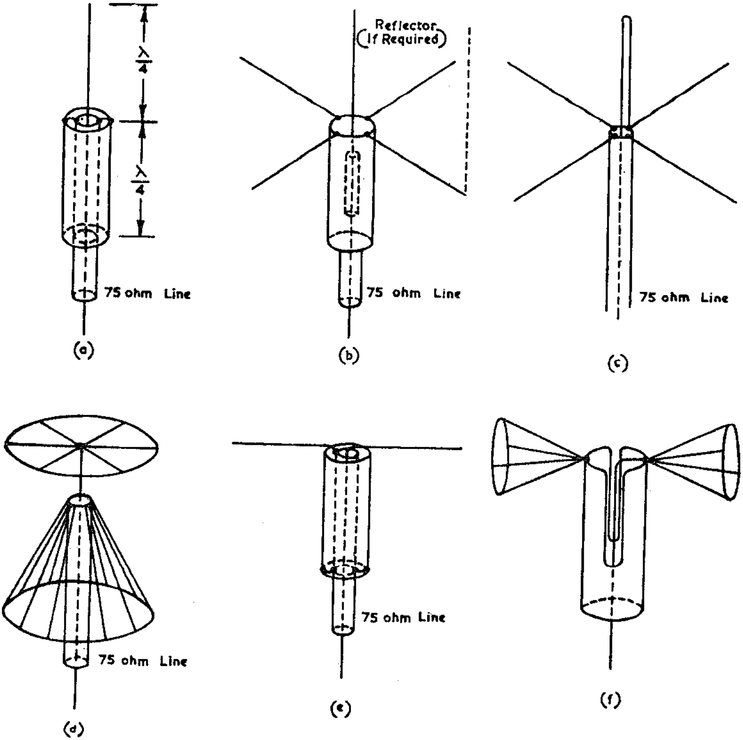

FIG. 22.12

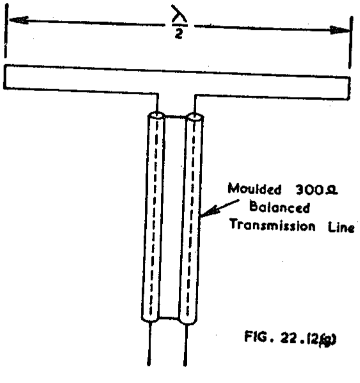

FIG. 22.12(g)

Fig. 22.12. *Some varieties of v-h-f aerials.*

(f) Is a modification of (e). The aerial conductors are made in the form of a conical cage to increase the frequency-range over which the aerial is effective. In this aerial another method of providing the transformation from the unbalanced transmission line to the balanced dipole is shown. It consists of splitting the outer conductor of the co-axial line into halves, for a distance of one quarter-wave. At the top of this " split " the halves of the dipole are connected directly to the outer conductor, while the inner conductor of the transmission line is connected to one of them.

One of the most easily constructed aerials is the folded half-wave dipole, which is shown in Fig. 22.12 (g). Whilst the radiation characteristic is the same as that of a conventional half-wave dipole, the folding produces an impedance transformation. When the conductors are of the same diameter throughout, the input impedance of the aerial is approximately 300 ohms. This enables the aerial to be matched directly to a 300 ohms moulded transmission line, which is commercially available. The spacing between the parallel conductors is not critical but, as in the case of a transmission line, it must be very small compared with a wavelength.

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Additional references will be found in the *Supplement commencing* on page 1475.